# ISO OBSERVATIONS OF AGB AND POST-AGB STARS

L.B.F.M. Waters[1,2], D.A. Beintema[2], J. Cami[1,2], Th. de Graauw[2], S. Hony[1], T. de Jong[3,1], K. Justtanont[4], F. Kemper[1], A. de Koter[1], J. Th. van Loon[1], F.J. Molster[1], A.G.G.M. Tielens[2], C. Waelkens[5], H. Van Winckel[5] & I. Yamamura[1]

[1]Astronomical Institute, University of Amsterdam, The Netherlands
[2]SRON Laboratory for Space Research Groningen, The Netherlands
[3]SRON Laboratory for Space Research Utrecht, The Netherlands
[4]Stockholm Observatory, 13336 Saltsjöbaden, Sweden
[5]Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Belgium

ABSTRACT

We review some of the highlights of the ISO observing programmes dedicated to the photospheres and winds of late-type stars. The ISO mission has provided for the first time an unbiased view of the gas-phase molecular components in the extended atmospheres of cool stars. The transition region between the photosphere and the cool outer layers was detected by means of spectroscopy. Several new molecules have been discovered. Also, a very rich harvest of new solid state emission bands was discovered. The detection of crystalline silicates in AGB and post-AGB stars is one of the surprises of the ISO mission. ISO also showed that the co-existence of C-rich and O-rich circumstellar material is much more common than previously believed. Observations of AGB stars in the Magellanic Clouds show that C-rich AGB stars can reach very high luminosities.

Key words: AGB stars; circumstellar matter; stellar winds.

## 1. INTRODUCTION

The launch in 1995 of the Infrared Space Observatory (ISO) has had a profound impact on the study of late stages of stellar evolution. This is because the instruments on board ISO were particularly well suited to study the photospheres and circumstellar envelopes of red giants (RGS), stars on the Asymptotic Giant Branch (AGB) and their more massive counterparts, the Red Supergiants (RSG), as well as post-AGB stars and Planetary Nebulae (PNe). These classes of objects radiate most of their energy in the ISO wavelength range, and important diagnostic tools such as gas-phase molecular bands, ionic forbidden lines and solid state bands are readily observable with ISO. Molecular bands are sensitive probes of the chemical composition and atmospheric structure (including the stellar wind), and ionic forbidden lines observed in PNe give new constraints on the chemical evolution of low and intermediate mass stars. Solid state bands reveal important clues about the composition and temperature of the dust that condenses in the outflows. The interplay between pulsations and radiation pressure on newly formed dust is probably responsible for driving the stellar winds of AGB stars. In order to better understand the physical and chemical processes that determine the structure of the atmosphere and that drive the wind, reliable measurements of these layers were badly needed, and ISO has provided a wealth of new information, most of which still needs to be digested.

This review summarizes some of the results obtained so far; given the limited space available, it is impossible to be complete. For more detailed overviews, we refer to the proceedings of IAU symposium 191, AGB Stars (Montpellier, 1998) editors T. Le Bertre, A. Lebre and C. Waelkens (ASP conf. series), and to the proceedings of the ISO conference 'ISO's View on Stellar evolution', Astrophysics & Space Science Reviews vol. 255 (eds. L.B.F.M. Waters, C. Waelkens, K.A. van der Hucht & P.A. Zaal, 1998), as well as to the proceedings of the first ISO workshop on analytical spectroscopy, ESA SP-419, eds. A. Heras et al. (1998).

## 2. THE EXTENDED ATMOSPHERES OF COOL STARS

### 2.1. The photosphere and near-photospheric regions

Due to stellar pulsations, the outer atmospheres of cool giants and supergiants are much more extended than in the case of hydrostatic equilibrium. In these outer layers a complex chemistry occurs, resulting in the formation of solid particles (dust grains).

At near- and mid-infrared wavelengths (2-15 $\mu$m), the spectra of cool stars are characterized by strong absorption bands from simple molecules that are mainly

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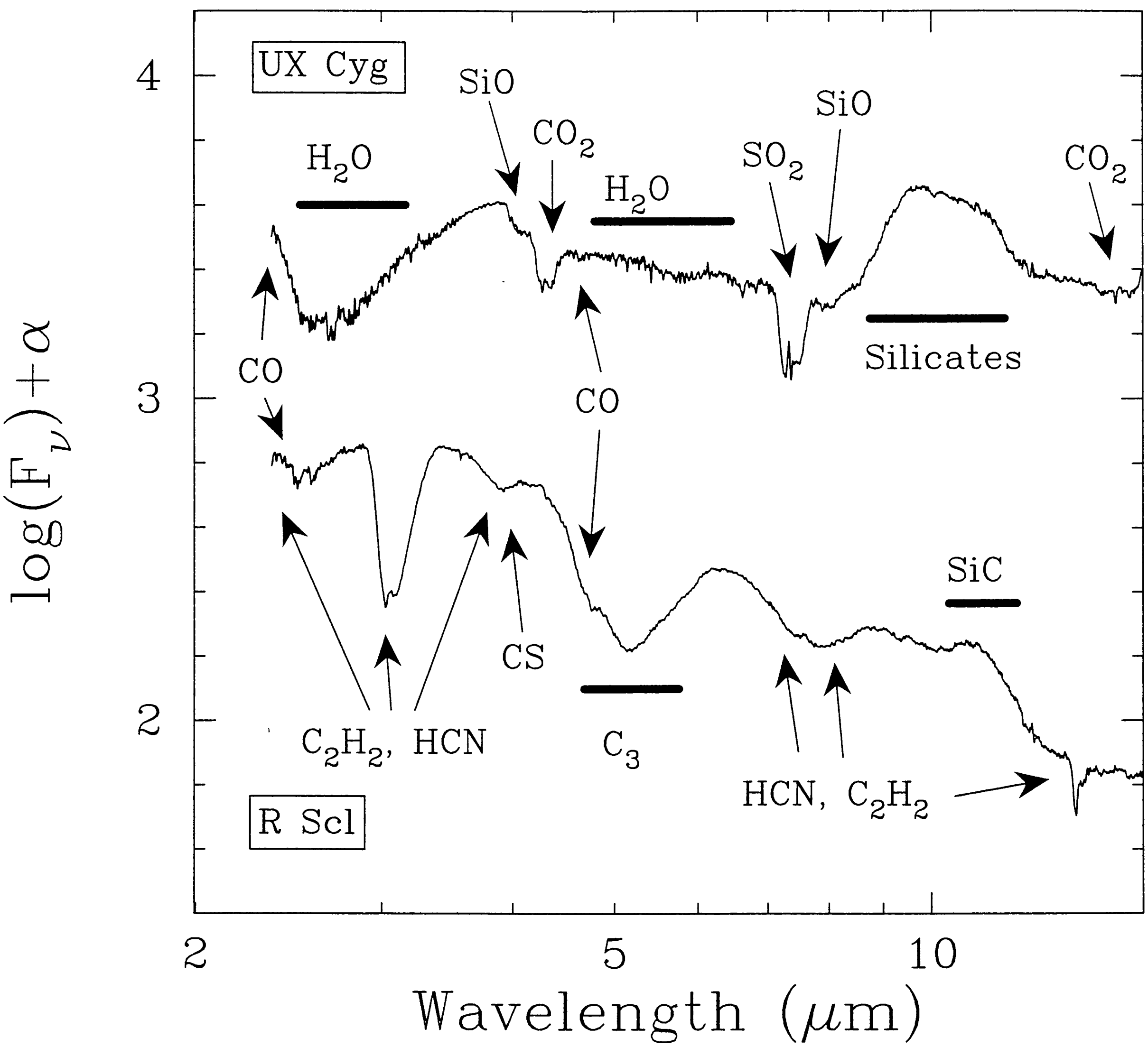


*Figure 1. Examples of SWS spectra of AGB stars with modest mass loss rates, UX Cyg (top, O-rich), and R Scl (bottom, C-rich). The strongest molecular absorption bands are indicated.*

formed in the photosphere. The kind of molecule that is observed is strongly dependent on the chemistry, more specifically the C/O ratio (see e.g. Gustafsson 1998 and references therein). CO, $CO_2$, SiO, OH and $H_2O$ are dominant if the C/O ratio is less than 1 (the M giants), while CO, CS, CH, HCN, $C_2H_2$, $C_2$, and SiS are abundant for C/O > 1 (the carbon stars). AGB stars evolve from O-rich (when they begin to ascend the AGB) to C-rich (towards the end of the AGB) as a result of mixing of carbon, produced by nuclear burning in shells surrounding the stellar core, into the atmosphere.

The ISO-SWS spectrograph allowed for the first time to obtain a full inventory of the strength and shape of these molecular absorption bands (see, e.g., Figure 1), and a comparison with model atmosphere predictions (e.g. Decin et al. 1998; Aoki et al. 1998a). The latter authors show that the appearance of molecular bands in carbon-rich SC and N-type stars correlates with the C/O ratio. CH was found to be strong in N type carbon stars, while the SiS first overtone band at 6.6 $\mu$m was only detected in one SC star. HCN is strong in SC stars, probably as a result of the lower C/O ratio and lower $T_{\rm eff}$ than N stars in their (small) sample.

The comparison between models and observations revealed some clear discrepancies in the strength and depth of some of the $H_2O$, SiO first overtone, $CO_2$ and CO fundamental absorption bands in M giants (e.g., Tsuji et al. 1997; see also Tsuji, these proceedings) and of the CS first overtone and CO fundamental in carbon stars (Aoki et al. 1998a). Such discrepancies can be explained by assuming that there is an extended layer of warm (T $\approx$ 1000 K), high-density ($10^{11}$ cm$^{-3}$) material on top of the photosphere, probably extending out to a few stellar radii, but still inside the dust forming region. This layer may be

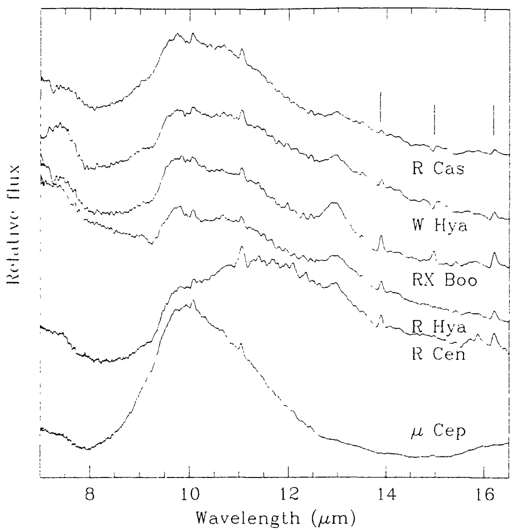


*Figure 2. SWS spectra of some M giants with $CO_2$ emission (Justtanont et al. 1998) and the 13 μm emission band, attributed to $Al_2O_3$. Note also the large variety in appearance of the 10 μm silicate band.*

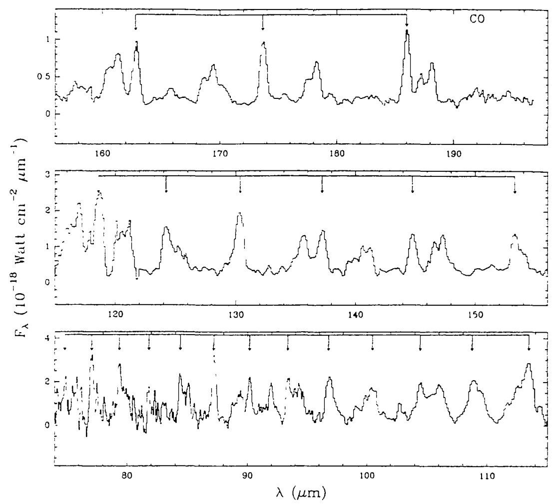


*Figure 3. Continuum subtracted LWS spectrum of the C-rich AGB star IRC+10216, with a wealth of emission lines from highly excited CO, and from HCN (Cernicharo et al. 1996)*

considered as part of the extended atmosphere. However, *spherical static* model atmospheres of M giants can in some cases fit the observed absorption bands (see e.g. Decin et al. 1998) of semi-regular variables with low mass loss rates and low pulsation amplitudes, without the need of an additional extended layer. Also, incomplete line lists can sometimes result in too weak absorption bands.

Justtanont et al. (1998; Figure 2) and Ryde et al. (1998; 1999) report the discovery of gas-phase $CO_2$ absorption and emission in M giants in the bending mode transitions of $CO_2$ in the 12 to 17 μm wavelength region. The presence of the 13 μm solid state emission band (attributed to $Al_2O_3$) seems correlated with the occurrence of $CO_2$ emission. The $CO_2$ emission bands can be well reproduced using a simple LTE model for its excitation, and points to a layer close to the stellar photosphere with densities of the order of $10^9$ to $10^{10}$ $cm^{-3}$, while excitation temperatures of 600-1200 K were found (Justtanont et al. 1998). These numbers depend somewhat on the (uncertain) abundance and thickness of the layer. Ryde et al. (1999) suggest that the $CO_2$ bands may not be in LTE, and fit the observations with two layers, one close to the star with high temperature and density, and a second layer which extends through the wind and has much lower temperature.

Recently, Yamamura et al. (1999a) published the first detection of gas-phase $SO_2$ at 7.3 μm in the O-rich AGB stars UX Cyg, Mira, and T Cep. Both absorption and emission was found, and for T Cep several spectra taken during two pulsation cycles showed a remarkable transition from emission to absorption. These observations suggest that the $SO_2$ is formed outside the atmosphere in a layer whose size varies with time, and with temperatures and densities of the order of 600 K and $10^9$ to $10^{11}$ $cm^{-3}$, respectively. Yamamura et al. (1999a) propose that the variation in the $SO_2$ in T Cep is a result of the its dissociation involving a mild UV radiation field which irradiates a high-density molecular layer extending a few stellar radii from the photosphere.

Spectroscopy in the 20-35 μm wavelength range of both O-rich and C-rich AGB stars revealed the presence of emission lines from [SI] (λ 25.25 μm), [FeI] (λ 24.04 μm), [FeII] (λ 25.99 and 35.35 μm), and [SiII] (λ 34.81 μm) (Aoki et al. 1998b). Similarly, forbidden emission lines were found in some RSG spectra by Justtanont et al. (1999). These emission lines must be formed in a layer where the metals are still in the gas phase and not incorporated into solid particles. Also, irradiation by a mild UV radiation field is needed, and the line flux ratios indicate that the density in that layer typically is $10^9$ $cm^{-3}$ (depending on the assumed radial extent of the layer). These observational properties strongly suggest that this layer is close to the photosphere.

While the evidence for an extended warm molecular layer in AGB stars based on *absorption bands* (e.g. CO, SiO, $H_2O$) is still a matter of debate, the $CO_2$, $SO_2$, and forbidden line emission data summarized above all point to a high-density layer of molecular gas extending to several stellar radii above the photosphere, and to the presence of a radiation field which produces some UV photons. The presence of the dense, warm molecular layer is probably linked to the stellar pulsations that permeate this part of the atmosphere and significantly affect the atmospheric scale-height.

Dynamical models of AGB atmospheres, including the onset of the stellar winds, have now reached a state of sophistication that allows direct comparison to observations. Hron et al. (1998) compare two SWS spectra of the C-star R Scl taken at different phases of the pulsation cycle to predictions based on the models by Höfner & Dorfi (1997). While there is good qualitative agreement between models and observations, detailed changes in the band strengths of, e.g., $C_2H_2$ are not yet understood.

Yamamura et al. (1998; 1999b) discuss the strength and formation region of the absorption bands seen in the 14 $\mu$m spectral region of C-rich AGB stars. These bands are due to bending modes of C-H bonds, mostly of $C_2H_2$ (see also Cernicharo 1998). Yamamura et al. (1999b) find that two layers contribute to the band strength: a warm layer at T $\approx$ 1200 K is found for all stars in the sample, while for high mass loss stars a second, much cooler layer is present. This cooler layer is probably located in the stellar wind, where dust grains have already been formed. The abundance of $C_2H_2$ in the cool layers was found to be similar to that of the inner warm regions, suggesting that no significant depletion of $C_2H_2$ onto dust grains going from the warm to the cool layers takes place. This could imply that $C_2H_2$ does not play a major rôle in the dust forming process, or that the bulk of the dust has already been formed at higher temperature. Model spectra calculated by Loidl et al. (1999), based on dynamical atmosphere calculations of Höfner et al. (1999), show that the depletion of $C_2H_2$ from the gas phase due to dust grain formation could begin at temperatures significantly higher than 1200 K. The lack of further depletion of $C_2H_2$ reported by Yamamura et al. (1999b) is consistent with these calculations. The presence of cool gas-phase $C_2H_2$ in the winds of high mass loss carbon stars demonstrates that not all $C_2H_2$ is depleted onto grains.

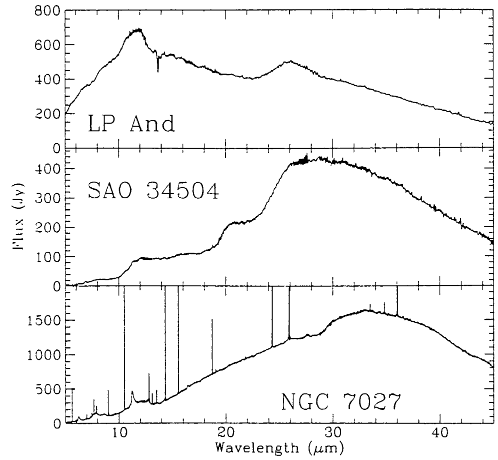


*Figure 4. SWS spectra showing the possible evolution of carbon-rich circumstellar dust along the AGB. Shown are LP And (AGB), SAO 34504 (young protoplanetary nebula) and NGC 7027 (PN). The strong narrow peaks are fine-structure emission lines from the ionized gas in NGC7027.*

### 2.2. Molecular emission and absorption from the stellar wind

At wavelengths longward of 15-20 $\mu$m, the spectra of AGB stars are fairly smooth if the mass-loss rates are low. For higher mass loss rates, line emission from high rotational levels of CO, HCN or $H_2O$ are prominent and are clearly detected with the SWS and LWS. Justtanont et al. (1996) showed that $H_2O$ pure rotational line emission is prominent in the M supergiant NML Cyg. Neufeld et al. (1996) and Barlow et al. (1996) showed that the spectrum of W Hya is very rich in $H_2O$ emission lines, and that they dominate the cooling of the gas in the outflow. Similarly, the LWS spectrum of IRC+10216 (Cernicharo et al. 1996; see Figure 3) is dominated by emission from rotational lines of CO and HCN (and some $^{13}CO$ and $H^{13}CN$). HCN dominates the cooling of the gas in the wind of IRC+10216 due to its very rich spectrum. In contrast, the LWS spectrum of the C-rich post-AGB star CRL 2688 is dominated by shock-excited CO lines ($T_{exc}$ = 400 K; Cox et al. 1996); CO provides the dominant cooling in this object. The lack of fine-structure lines suggests that the central star is not yet hot enough to form a Photon Dominated Region (PDR).

Justtanont et al. (1996) and Sylvester et al. (1997) report the detection of OH line absorption at 34.6 $\mu$m in the M supergiant NML Cyg and the post-red-supergiant IRC+10 420. In the latter star, OH emission at 79.2, 98.7, 119.3 and 163.2 $\mu$m was also detected. Sylvester et al. (1997) confirm that the OH absorption at 34.6 $\mu$m is responsible for pumping the OH maser at 1665, 1667 and 1612 GHz, as was proposed by Shklovsky (1966) and Elitzur et al. (1976). In IRC+10 420 a pump efficiency of the order of 3 per cent was found. Thai-Q-Tung et al. (1998) present a radiative transfer model for the excitation of the OH maser in IRC+10420 and find a good match with the ISO data.

## 3. SOLID STATE BANDS

The ISO spectra of AGB and post-AGB stars have revealed a very rich harvest of new solid state emission and absorption bands. We briefly discuss the C-rich and O-rich sources.

### 3.1. C-rich sources

In Figure 4 we show the SWS spectra of 3 C-rich evolved stars, the AGB star LP And, the post-AGB star SAO 34504 and the PN NGC7027. It is apparent from Figure 4 that there are significant changes in the appearance of the solid state bands going from AGB to PN. C-rich AGB stars are dominated by the presence of SiC near 11.3 $\mu$m, seen in emission and in absorption. At longer wavelengths, and for stars with high mass loss rates, the 30 $\mu$m feature is apparent, and peaks at wavelengths significantly shortward of 30 $\mu$m. This 30 $\mu$m band has been attributed to MgS (e.g. Goebel & Moseley 1985; Begemann et al. 1994). So far no unidentified IR (UIR) emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 $\mu$m have been found in C-rich AGB stars.

Post-AGB stars and PNe show a very rich solid state emission structure. The SWS spectrum of SAO34504 (Figure 4) has prominent bands near 8 and 12 $\mu$m, probably due to carbon-bearing solids. In addition, a weak emission band near 16 $\mu$m is seen, as well as

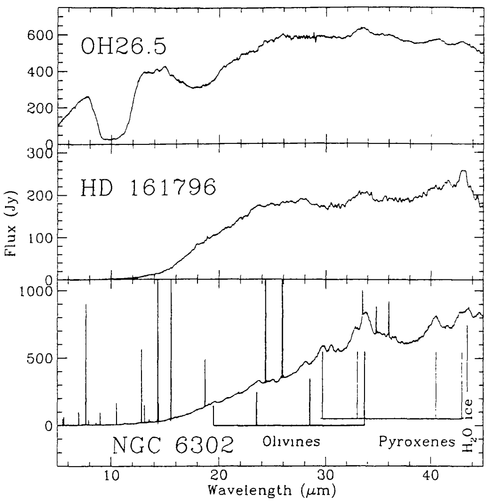


*Figure 5. SWS spectra of O-rich evolved stars. Shown are OH26.5 (OH/IR star with heavy mass loss), HD 161796 (young proto-planetary nebula), and NGC6302 (bipolar planetary nebula). Notice the rich solid state spectrum of crystalline silicates in all three sources.The strong narrow peaks are fine-structure emission lines from the ionized gas in NGC6302.*

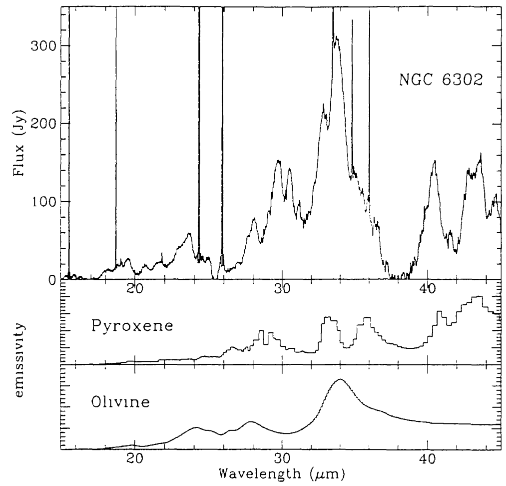


*Figure 6. Continuum subtracted SWS spectrum of NGC6302, showing prominent solid state emission bands due to crystalline silicates. Underplotted are laboratory spectra of olivine and pyroxene (Jäger et al. 1998; Koike & Shibai 1998) with low Fe content, and weighed with a blackbody of 60 K.*

the well-known 21 $\mu$m and 30 $\mu$m bands. The identification of the 21 $\mu$m feature, while clearly linked to a carbonacious carrier, is still far from settled: among others, glassy $SiS_2$ (Begemann et al. 1996) and nano-diamonds (Hill et al. 1998) have been proposed. Note that $SiS_2$ has a second band near 16.5 $\mu$m (Begemann et al. 1996), which may be related to the 16 $\mu$m band seen in SAO34504. However, this 16.5 $\mu$m band is not seen in some other sources with 21 $\mu$m feature. The 21 $\mu$m band has not been seen in C-rich AGB stars (both with low and high mass loss), nor in C-rich PNe, while the 30 $\mu$m feature is prominent in e.g. NGC 7027 (Beintema 1998, Figure 4). We note that the peak wavelength of the 30 $\mu$m feature shifts significantly from AGB to PN. This wavelength shift may be due to differences in grain size and/or shape, or to differences in composition (e.g. core-mantle grains).

### 3.2. O-rich sources

In the 3 to 20 $\mu$m wavelength range of post-AGB and PNe spectra, a rich emission spectrum from UIR bands is observed (Molster et al. 1996; Beintema et al. 1996a, 1998). These UIR bands are commonly attributed to Polycyclic Aromatic Hydrocarbons (PAHs). We refer to the review by Tielens et al. (these proceedings) for more details concerning circumstellar PAHs. Surprisingly, no PAH emission was detected in the evolved C-rich PN NGC7293 (the Helix Nebula, Cox et al. (1998)), but instead the 5 to 15 $\mu$m spectral region, observed with the ISOCAM CVF, showed strong emission from $H_2$ rotational line transitions and no appreciable dust continuum. Cox et al. (1998) conclude that the absence of PAH emission and continuum radiation from small grains implies that these grains have been destroyed, possibly by the intense UV and soft X-ray radiation field of the hot central star.

These ISO observations beautifully demonstrate the remarkable change in appearance of solid state bands, and hence in dust composition, going from AGB to PN in C-rich objects. The nature of the dust returned to the ISM therefore also strongly depends on the evolutionary phase of the underlying star. The lack of PAH emission in the Helix Nebula opens the possibility that PNe may not be the (dominant) source of PAHs in the ISM.

The dust in oxygen-rich stars is dominated by emission at 10 and 18 $\mu$m due to the Si-O stretching and O-Si-O bending mode in amorphous silicates. A considerable variation in the shape and strength of these bands can be seen (Figure 2), indicating the presence of varying amounts of elements as Ca, Al, and Na in the grains. In particular the inclusion of Al shifts the 10 $\mu$m band to longer wavelength (Tielens 1990; Mutschke et al. 1998). M giants with modest mass loss rates show a prominent 13 $\mu$m feature (Sloan et al. 1996) attributed to $Al_2O_3$ (e.g. Onaka et al. 1989; Begemann et al. 1997) or possibly to $Al_2O_3$ coated with silicates (Kozasa & Sogawa 1998).

A great surprise was the discovery of numerous narrow emission bands in the 10-70 $\mu$m SWS and LWS spectra (Figures 5, 6 and 7) of stars with cool circumstellar dust. These bands can be attributed to crystalline silicates (Waters et al. 1996; Barlow 1998). Before ISO the occurrence of crystalline silicates was only known for solar system comets (e.g., Hanner et al. 1994) and in the proto-planetary disk system $\beta$ Pic (Knacke et al. 1993). The high quality ISO spectra now convincingly show the presence of these

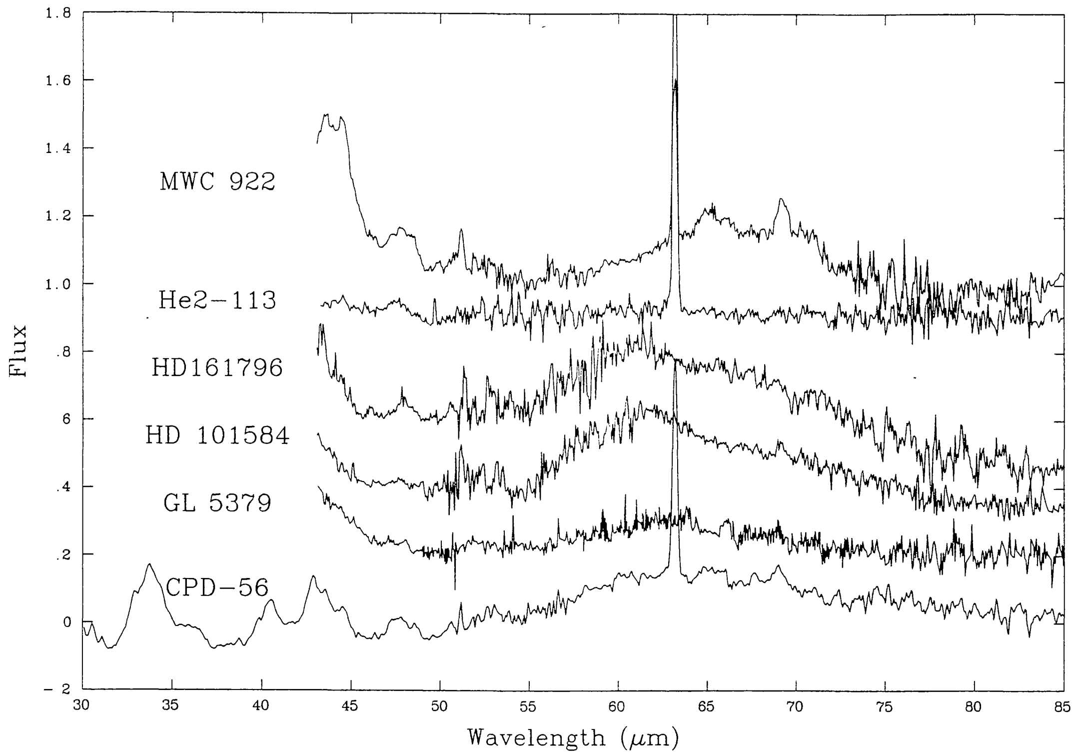


*Figure 7. Continuum subtracted LWS spectra of several evolved stars with cool dust shells (Barlow 1998). The narrow emission near 69 $\mu$m is due to forsterite, and the broad peak near 60 $\mu$m due to crystalline $H_2O$ ice. The 60 $\mu$m bump may also have a contribution from clino-pyroxene. A feature near 47.5 $\mu$m is unidentified.*

bands in a number of sources, including evolved stars as well as young stars (see also the contribution of Waelkens et al. in these proceedings).

The narrow emission bands are prominent in sources with colour temperatures less than about 200 K (with some notable exceptions). A comparison between observations and laboratory spectra of olivines ($Mg_{2x}Fe_{2-2x}SiO_4$) and pyroxenes ($Mg_xFe_{1-x}SiO_3$) (Koike et al. 1993; Koike & Shibai 1998; Jäger et al. 1998; Molster et al. 1999; Cohen et al. 1999; see also Figure 6) indicates that the minerals are Fe-poor and Mg-rich. The 69 $\mu$m olivine feature (Barlow 1998) is particularly sensitive to the Mg/Fe ratio, since it already shifts to longer wavelengths by 3 $\mu$m when a few per cent of Fe is included. The observed wavelength of 69 $\mu$m in several sources therefore suggests that the composition of the olivine is $Mg_2SiO_4$ (pure forsterite). Similarly, the wavelength of the 40.5 $\mu$m peak of pyroxenes is very sensitive to the Fe/Mg ratio and is well matched assuming the Mg-rich end member $MgSiO_3$ (enstatite). The observed band widths are narrower than the bands seen in the laboratory spectra. Grain size and shape effects would tend to broaden the laboratory spectra, and thus cannot explain the differences. Perhaps the circumstellar grains have fewer lattice defects than the laboratory materials (Jäger, private communication).

The presence of prominent crystalline silicate bands in stars with on-going high mass loss (Waters & Molster 1999) suggests that these grains are produced in the dust forming layers close to the photosphere. Abundances vary but are typically only a few per cent to 10-15 per cent, i.e. the amorphous silicate grains are by far the most abundant component. Stars with low mass loss rates do not show evidence for crystalline silicates.

The formation of these Mg-rich crystalline grains is not clear. It is possible that Mg-rich grains in the outflows of M giants form above the glass temperature. After cooling to lower temperatures, a reaction with Fe can occur resulting in the adsorption of Fe into the grains, whose lattice structure becomes amorphous as a result (Tielens et al.1998). Alternatively, Kozasa & Sogawa (1999) propose that crystalline mantles can form on cores of $Al_2O_3$ for high mass loss rates. However, this mechanism does not explain the low Fe content.

The SWS and LWS spectra of oxygen-rich stars also show the presence of emission near 43 $\mu$m and 60 $\mu$m (Figure 7, Barlow 1998). These features can be attributed to crystalline $H_2O$ ice (amorphous ice does not show a 60 $\mu$m peak). These bands were previously seen with KAO in a small number of sources (Omont et al. 1990). There is considerable variation in the shape of the 60 $\mu$m band, which may be due to a blend with clino-enstatite, which shows a rather broad 65 $\mu$m band (Koike & Shibai 1998). Note also that the peak of the 60 $\mu$m crystalline $H_2O$ band depends somewhat on temperature (Bertie & Whalley 1967), but not enough to explain the observed range. The 43 $\mu$m band blends with crystalline pyroxene.

## 4. CARBON-RICH OBJECTS WITH OXYGEN-RICH DUST

The presence of crystalline silicates in circumstellar shells, with prominent spectral signatures beyond 20 $\mu$m, opens the possibility to determine the chemical composition of cool dust. This has resulted in some remarkable discoveries of cool oxygen-rich dust in the surroundings of carbon-rich stars. We discuss two cases: [WC] central stars of PNe, and the Red Rectangle (RR).

The class of [WC] PNe have a C-rich, He-rich and H-poor central star, surrounded by a C-rich nebula which often still contains H. Many [WC] PNe have rather warm dust shells dominated by PAH emission and a smooth underlying continuum. The temperature of the main dust component suggests that these stars have recently stopped losing mass and have evolved rapidly (within $\approx 10^3$ years) from the AGB to high ($T_{\rm eff}$ >25000 K) temperatures. The lack of appreciable H in their atmosphere is probably related to a late thermal pulse, which the star experienced at the very end of the AGB or just after it left the AGB. This presumably resulted in extensive mixing and mass loss, and may have removed any remaining H in the atmosphere. However, evolutionary calculations have some difficulty explaining the [WC] PNe with warm, massive dust envelopes. A thermal pulse at the very end of the AGB or shortly after the AGB may result in a change from O-rich to C-rich, but the stellar envelope in these models is still too massive to burn all H in the thermal pulse (see. e.g. Blöcker & Schönberner 1997). Hence a C-rich, and H-rich atmosphere is predicted, but not observed.

ISO spectroscopy of [WC] PNe has revealed the presence of emission from crystalline silicates at wavelengths longward of 20 $\mu$m (Waters et al. 1998a; Szczerba et al. 1998; Barlow 1998; Cohen et al. 1999). This indicates that (part of) the cool dust in these nebulae is in fact O-rich (silicates), while the inner nebula and the central stars are C-rich. Waters et al. (1998a) and Cohen et al. (1999) propose that this change of chemistry is expected as a result of a thermal pulse. This would strongly support evolutionary scenarios that link the formation of [WC] PNe to a late thermal pulse. Cohen et al. (1999) also discuss the possibility that the crystalline grains in [WC] stars are the result of the destruction of Kuiper-belt objects as the star evolved on the AGB. If the presence of O-rich dust in PNe is restricted to [WC] central stars (as currently believed), the Kuiper belt scenario is less likely.

The C-rich PN NGC7027, although not classified as a [WC] central star of a PN, was reported to have $H_2O$ water vapour line emission at 179.53 $\mu$m (Liu et al. 1996), but a re-analysis of the LWS spectrum showed that $CH^+$ is in fact responsible for this emission (Cernicharo et al. 1997). The $CH^+$ and CH

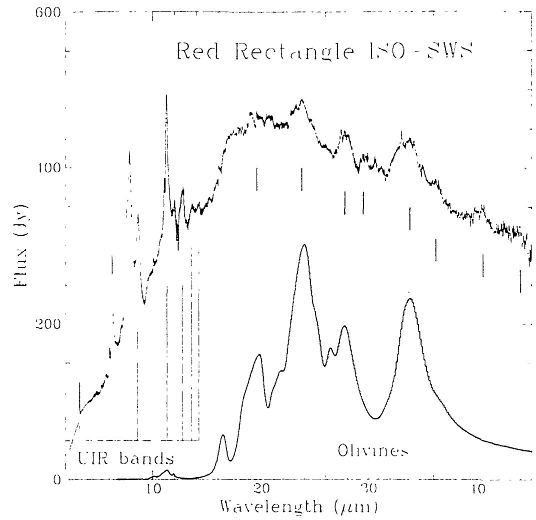


*Figure 8. SWS spectrum of the Red Rectangle (Waters et al. 1998). The 3-12 $\mu$m wavelength region is dominated by UIR band emission from the C-rich nebula. At longer wavelengths, emission from crystalline silicates dominates. These grains are probably in the circum-binary disk.*

detection (Liu et al. 1997) in NGC7027 gives important constraints on the photochemistry in the C-rich PDR. So far no evidence for silicates in NGC7027 has been found.

The Red Rectangle (HD 44179, RR) has long been considered as the prototype of the carbon-rich protoplanetary nebulae. It was discovered in 1975 by Cohen et al. as a rectangularly shaped nebula with prominent Extended Red Emission in its optical spectrum. Infrared spectroscopy revealed strong UIR band emission (Russel et al. 1978), while high resolution optical and near-IR imaging showed that the central star is hidden by a thick dusty disk (e.g. Roddier et al. 1995). Radial velocity studies showed the presence of a single-lined spectroscopic binary in a wide orbit (Waelkens et al. 1996); the dusty disk surrounds the entire binary system. SWS spectroscopy showed that the 20-45 $\mu$m SWS spectrum is dominated by emission from crystalline silicates (Figure 8, Waters et al. 1998b). In addition, absorption from gas-phase $CO_2$ at 4.27 and 15 $\mu$m was detected. Ground-based imaging in the UIR bands showed that the UIR emission is more concentrated in the extended X-shaped nebula, while the ISO data suggest that the crystalline dust and the $CO_2$ gas are likely located in the circum-binary disk (Waters et al. 1998b).

The observations are consistent with an evolutionary scenario in which the more massive star in the system evolved on the AGB and developed a dense, *oxygen-rich* wind. Some of this material never escaped the system but was stored in a circum-binary disk. Subsequently the AGB star evolved to a C-rich phase and created the C-rich nebula inside the oxygen-rich disk. The present-day gas and grain properties in the long-lived disk of the RR (large grains, crystalline silicates, CO depletion) suggest significant grain processing, similar to that seen in the disks surrounding young objects. Recent observations by Jura & Turner (1998) indicate that the similarity may go as far as actual planet formation in the RR disk.

The RR is part of a group of objects with relatively high abundance of crystalline silicates. These sources have in common that the dust is in a long-lived disk surrounding a single star or a binary (e.g. 89 Her, AC Her). These observations suggest that the degree of crystallinity of dust increases with time. Note that mass-losing AGB stars with high mass loss rates have low abundance of crystalline silicates. While the mechanism causing dust crystallinity in these mass-losing AGB stars is likely related to the high temperatures in the dust forming layers, the physical mechanism that causes the high crystalline dust abundances in 'disk sources' is not clear. For instance, at the observed dust temperatures of 100 to 200 K, the annealing timescale for amorphous dust is prohibitive.

## 5. AGB STARS IN THE MAGELLANIC CLOUDS

The sensitivity of ISO for the first time allowed detailed studies of populations of AGB stars in the Magellanic Clouds (MCs), both using photometry and spectroscopy (ISOCAM CVF and ISOPHOT-S). The study of AGB stars in the MCs has the great advantage that distance and luminosity are known, contrary to galactic sources (see also Blommaert et al., these proceedings). Trams et al. (1999a) report the discovery of the first C star with oxygen-rich dust shell in the LMC, and Trams et al. (1999b) and van Loon et al. (1999) determine the chemical type (O-rich or C-rich) for a large sample of infrared-bright AGB stars in the LMC. They show that very luminous C-rich AGB stars exist up to the limit for AGB stars. These observations put strong constraints on the efficiency of hot bottom burning; this mechanism can suppress the formation of luminous C-rich AGB stars by the conversion of C to N through CNO burning near the bottom of the envelope.

ISOCAM imaging of clusters in the MCs by Tanabé et al. (1998) has resulted in the detection of several very red stars not seen at optical wavelengths, but with bolometric luminosities around -4.5. Such values for $M_{bol}$ are expected given the age of these clusters (more than $10^9$ yr), but the very high mass loss rates are nevertheless surprising. These observations demonstrate that even stars with low initial mass can reach very high mass loss rates at the tip of the AGB.

## 6. SUMMARY

The very rich harvest of new data on late stages of evolution obtained by ISO has already had a significant impact on our understanding of the structure of the atmospheres and winds of late type stars. Much more work, both observational and in the laboratory, is needed to take full advantage of the ISO data. Looking ahead, it is clear that there are many new questions raised that need new instrumentation to clarify. High spectral and spatial resolution observations of molecular lines (e.g., with the heterodyne receivers on board of FIRST, e.g., HIFI, and with the large millimeter arrays planned by the US and Europe) will allow much more detailed studies of the distribution and kinematics of these species in the extended envelopes of AGB stars. Also, high spatial resolution observations at infrared wavelengths (e.g. with the VLT and with the VLT interferometer) at modest spectral resolution will give more insight in the structure of the atmosphere and the location of dust formation as a function of stellar pulsation. The VLT will also provide deep imaging at 10 $\mu$m and 20 $\mu$m of populations of stars in external galaxies.

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## REFERENCES

Aoki. W., Tsuji, T., Ohnaka, K. 1998a, A&A 340, 222

Aoki, W., Tsuji, T., Ohnaka, K. 1998b, A&A 333, L19

Barlow, M.J., Nguyen-Q-Rieu, Truong-Bach, et al. 1996, A&A 315, L241

Barlow M.J. 1998, Astrophys. Sp. Sc. 255, 315

Begemann, B., Dorschner, J., Henning, Th., Mutschke, H., Thamm, E.: 1994, ApJ 423, L71

Begemann, B., Dorschner, J., Henning, Th., Mutschke, H. 1996, ApJ 464, L195

Begemann, B., Dorschner, J., Henning, Th., Mutschke, H., Gürtler, J., Kömpe, C., Naas, S. 1997, ApJ 476, 199

Beintema, D.A. 1998, Astrophys. Sp. Sc. 255, 507

Beintema, D.A., van den Ancker, M.E., Molster, F.J., Waters, L.B.F.M., Tielens, A.G.G.M., Waelkens, C., de Jong, T., de Graauw, Th., Justtanont, K., Yamamura, I., Heras, A., Lahuis, F., Salama, A. 1996, A&A 315, L369

Bertie, J.E., Whalley, E. 1967, Journal of Chem. Phys. 46, 1271

Blöcker, T., & Schönberner D. 1997, A&A 324, 991

Cernicharo, J., Barlow, M.J., González-Alfonso, E., et al. 1996, A&A 315, L201

Cernicharo, J., Liu, X.-W., González-Alfonso, E., Cox, P., Barlow, M.J., Lim, T., Swinyard, B.M. 1997, ApJ 483, L65

Cernicharo, J. 1998, Astrophys. Sp. Sc. 255, 303

Cohen, M. Anderson, C.M., Cowley, A., Coyne,G.V., Fawley, W.M., Gull, T.R., Harlan, E.A., Herbig, G.H., Holden, F., Hudson, H.S., Jakoubek, R.O., Johnson, H.M., Merrill, K.M., Schiffer, F.H., Soifer, B.T., Zuckerman, B. 1975, ApJ 196, 179

Cohen, M., Barlow, M.J., Sylvester, R.J., Liu, X.-W., Cox, P., Lim, Schmitt, B., Speck, A.K. 1999, ApJ (in press)

Cox, P., González-Alfonso, E., Barlow, M.J., et al. 1996, A&A 315, L265

Cox, P., Boulanger, F., Huggins, P.J., Tielens, A.G.G.M., Forveille, T., Bachiller, R., Cesarsky, D., Jones, A.P., Young, K., Roelfsema, P.R., Cernicharo, P. 1998, ApJ 495, L23

Decin, L., Cohen, M., Eriksson, K., Gustafsson, B., Huygen, E., Morris, P., Plez, B., Sauval, J., Vandenbussche, B., Waelkens, C. 1998, in *First ISO workshop on Analytical Spectroscopy*, ESA SP-419, p. 185

Elitzur, M., Goldreich, P., Scoville, N. 1976, ApJ 205, 384

Goebel, J.H., Moseley, S.H. 1985, ApJ 290, L35

Gustafsson, B. 1998, Astrophys. Sp. Sc. 255, 241

Hanner, M.S., Lynch, D.K., Russell, R.W.: 1994, ApJ 425, 274

Hill, H.G.M., Jones, A.P., D'Hendecourt, L.B.: 1998, A&A 336, L41

Höfner, S., Dorfi, E.A.: 1997, A&A 319, 648

Höfner, S., Jorgensen, U.G., Loidl, R., Aringer, B.: 1999, A&A (in press)

Hron, J., Loidl, R., Höfner, S., Jorgensen, U.G., Aringer, B., Kerschbaum, F. 1998, A&A 335, L69

Jäger, C., Molster, C., Dorschner, J., Henning, Th., Mutschke, H., Waters, L.B.F.M. 1998, A&A 339, 904

Jura, M., Turner, J. 1998, Nature 395, 144

Justtanont, K., de Jong, T., Helmich, F.P., Waters, L.B.F.M., de Graauw, Th., Loup, C., Izumiura, H., Yamamura, I., Beintema, D.A., Lahuis, F., Roelfsema, P.R., Valentijn, E.A. 1996, A&A 315, L217

Justtanont, K.; Feuchtgruber, H.; De Jong, T., Cami, J., Waters, L.B.F.M., Yamamura, I., Onaka, T. 1998, A&A 330, L17

Justtanont, K., Tielens, A.G.G.M., de Jong, T., Cami, J., Waters, L.B.F.M., Yamamura, I.: 1999, submitted to A&A

Knacke, R.F., Fajardo-Acosta, S.B., Telesco, C.M., hackwell, J.A., Lynch, D.K., Russell, R.W. 1993 ApJ 418, 440

Koike, C., Shibai, H., Tuchiyama, A. 1993, MNRAS 264, 654

Koike, C., Shibai, H. 1998, Institute of Space and Astronautical Science, report no. 671

Kozasa, T., Sogawa, H. 1998, Astrophys. Sp. Sc. 255, 437

Kozasa, T., Sogawa, H. 1999, in proc. of IAU Symp 191, 'AGB stars', eds. T. Le Bertre, A. Lebre & C. Waelkens, ASP conf. series (in press)

Liu, X.-W., Barlow, M.J., Nguyen-Q-Rieu, et al. 1996, A&A 315, L257

Liu, X.-W., Barlow, M.J., Dalgarno, A., Tennyson, J., Lim., T., Swinyard, B.M., Cernicharo, J., Cox, P., Baluteau, J.-P., Péquignot. D., Nguyen-Q-Rieu, Emery, R.J., Clegg, P.E. 1997, MNRAS 290, L71

Loidl, R., Höfner, S., Jorgensen, U.G., Aringer, B. 1999, A&A (in press)

van Loon J.Th., Zijlstra A.A., Groenewegen M.A.T., A&A submitted

Molster, F.J., van den Ancker, M.E., Tielens, A.G.G.M., Waters, L.B.F.M., Beintema, D.A., Waelkens, C., de Jong, T., de Graauw, Th., Justtanont. K., Yamamura, I., Vandenbussche, B., Heras. A.M. 1996, A&A 315, L373

Molster, F.J., Waters, L.B.F.M., Trams, N.R., van Winckel, H., Decin, L., van Loon, J. Th., Jäger, C.. Henning, Th., Käufl, H.-U., de Koter, A., Bouwman, J. 1999, A&A (submitted)

Mutschke, H., Begemann, B., Doschner, J., Gürtler, J., Gustafson, B., Henning, Th., Stognienko, R. 1998, A&A 333, 188

Neufeld, D.A., Chen, W., Melnick, G.J., de Graauw, Th., Feuchtgruber, H., Haser, L., Lutz, D., Harwit, M. 1996, A&A 315, L237

Omont, A., Forveille, t., Moseley, S.H., Glaccum, W.J., Harvey, P.M., Likkel, L., Loewenstein, R.F., Lisse, C.M. 1990, ApJ 355, L27

Onaka, T., de Jong, T., Willems, F.J. 1989, A&A 218, 169

Roddier, F., Roddier, C., Graves, J.E., Northcott, M.J. 1995, ApJ 443, 249

Russel, R.W., Soifer, B.T., Willner, S.P. 1978, ApJ 220, 568

Ryde, N., Eriksson, K., Gustafsson, B., Lindquist, M., Olofsson, H. 1998, Astrophys. Sp. Sc. 255, 301

Ryde, N., Eriksson, K., Gustafsson, B. 1999, A&A 341, 579

Shklovsky, I.S. 1966, Astron. Tsirk., No. 372

Sloan, G.C., LeVan, P.D., Little-Marenin, I.R. 1996, ApJ 463, 310

Sylvester, R.J., Barlow, M.J., Nguyen-Q-Rieu, Liu, X.-W., Skinner, C.J., Cohen, R.J., Lim, T., Cox, P., Truong-Bach, Smith, H.A., Habing, H.J. 1997, MNRAS 291, L42

Szczerba, R., Górny, S.K., Tylenda, R. 1998, Astrophys. Sp. Sc. 255, 515

Tanabé, T., Nishida, S., Nakada, Y., Onaka, T., Glass. I.S., Sauvage, M. 1998, Astrophys. Sp. Sc. 255, 407

Thai-Q-Tung, Dinh-V-Trung, Nguyen-Q-Rieu, Bujarrabal, V., Le Bertre, T., Gérard, E. 1998, A&A 331, 317

Tielens, A.G.G.M. 1990, in From Mira's to Planetary Nebulae: which path for stellar evolution?', eds. M.O. Mennessier & A. Omont, Editions Frontières, page 186

Tielens, A.G.G.M., Waters, L.B.F.M., Molster, F.J., Justtanont, K. 1998, Astrophys. Sp. Sc. 255, 415

Trams N.R., van Loon J.Th., Zijlstra A.A., Groenewegen M.A.T., Waters L.B.F.M., Loup C., Blommaert J.A.D.L., Siebenmorgen R., Heske A., Whitelock P.A. 1999a, A&A (in preparation)

Trams N.R., van Loon J.Th., Waters L.B.F.M., Zijlstra A.A., Whitelock P.A., Groenewegen M.A.T., Loup C., Blommaert J.A.D.L., Siebenmorgen R., Heske A., Feast M.W. 1999b, A&A (submitted)

Tsuji, T., Ohnaka, K., Aoki, W., Yamamura, I. 1997, A&A 320, L1

Waelkens, C., van Winckel, H., Waters, L.B.F.M., Bakker, E.J. A&A 314, L17

Waters, L.B.F.M., Molster, F.J., de Jong, et al. 1996, A&A L361

Waters, L.B.F.M., Beintema, D.A., Zijlstra, A.A., de Koter, A., Molster, F.J., Bouwman, J., de Jong, T., Pottasch, S.R., de Graauw, Th. 1998a, A&A 331, L61

Waters, L.B.F.M., Waelkens, C., van Winckel, C., Molster, F.J., Tielens, A.G.G.M., van Loon, J. Th., Morris, P.W., Cami, J., Bouwman, J., de Koter, A., de Jong, T., de Graauw, Th. 1998b, Nature 391, 868

Waters, L.B.F.M., Molster, F.J. 1999, in Proc. IAU symp. 191, 'AGB stars", eds. T. Le Bertre, A. Lebre & C. Waelkens, ASP conf. series (in press)

Yamamura, I., de Jong, T., Justtanont, K., Cami, J., Waters, L.B.F.M. 1998, Astrophys. Sp. Sc. 255, 351

Yamamura, I., de Jong, T., Onaka, T., Cami, J., Waters, L.B.F.M. 1999a, A&A 341, L9

Yamamura, I., de Jong, T., Waters, L.B.F.M., Cami, J. 1999b, in Proc. IAU symp. 191, 'AGB stars', eds. T. Le Bertre, A. Lebre & C. Waelkens, ASP conf. series (in press)